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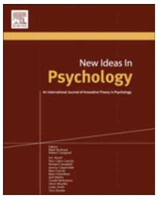
New Ideas in Psychology xxx (2013) 1–11

Contents lists available at SciVerse ScienceDirect

New Ideas in Psychology

journal homepage: www.elsevier.com/locate/newideapsych



Limitations of distal effect anticipation when using tools

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Keywords:
Tool use
Sensorimotor transformation
Action effect
Proprioception
Vision
Perception

ABSTRACT

Modern technologies progressively create workplaces in which the execution of movements and the observation of their consequences are spatially separated. Challenging workplaces in which users act via technical equipment in a distant space include aviation, applied medical engineering and virtual reality. When using a tool, proprioceptive/tactile feedback from the moving hand (proximal action effect) and visual feedback from the moving effect point of the tool, such as the moving cursor on a display (the distal action effect) often do not correspond or are even in conflict. If proximal and distal feedback were equally important for controlling actions with tools, this discrepancy would be a constant source of interference. The human information processing system solves this problem by favoring the intended distal action effects while attenuating or ignoring proximal action effects. The study presents an overview of experiments aiming at the underlying motor and cognitive processes and the limitations of visual predominance in tool actions. The main findings are, that when transformations are in effect the awareness of one's own actions is quite low. This seems to be advantageous when using tools, as it allows for wide range of flexible sensorimotor adaptations and – may be more important – it evokes the feeling of being in control. Thus, the attenuation of perceiving one's own proximal action effects is an important precondition for using tools successfully. However, the ability to integrate discordant perception-action feedback has limits, especially, but not only, with complex transformations. When feature overlap between vision and proprioception is low, and when the existence of a transformation is obvious proximal action effects come to the fore and dominate action control in tool actions. In conclusion action–effect control plays an important role in understanding the constraints of the acquisition and application of tool transformations.

1. Introduction

Modern technology progressively creates workplaces that spatially separate movement execution from observation. When using tools, proprioceptive/tactile feedback from the moving hand (proximal action effect) and visual feedback of the movement in external space (distal action effect) do often not correspond or are even in conflict. Computer input devices are one example in this regard. For instance, the computer mouse makes a rather simple transformation. Hand movement on the horizontal table surface is transformed into cursor movement on the vertical display. Making the relationship somewhat less direct, a constant or variable gain factor applied to the hand movement perturbs the cursor movement. But still, the relationship between hand amplitude and cursor amplitude is obvious. In more sophisticated tools, like those used

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http://dx.doi.org/10.1016/j.newideapsych.2012.12.001

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in aviation, applied medical engineering, and virtual reality, the relation can be quite complex and becomes less obvious. To operate rotary devices (e.g., a trackball) or force-sensitive devices (e.g., an isometric joystick), the agent has to learn an unfamiliar relation between an applied rotation or force (proximal effect) and a resulting cursor movement on the display (distal effect). In this case it is obvious to the agent that the visual feedback originates from transformed movements, and it is often observed that human movements become slow, inaccurate, and strenuous. The present paper focuses on basic understanding of the perception and action mechanisms in the use of tools with sensorimotor transformations. It provides a theoretical background and empirical evidence for the reciprocal influence of action on perception (e.g., Müsseler, 1999; O'Regan & Noë, 2001; Sutter, Müsseler, Bardos, Ballagas, & Borchers, 2008; in addition, an overview on cognitive representations of tool actions is provided by Massen (in this issue)).

The basic problem of integrating perception–action feedback is depicted in Fig. 1. In a human information processing system, sensorimotor transformations occur with various kinds of tool use. On the basis of the perceived body space and tool space a motor command is generated, which entails a movement of the corresponding effector. The bodily movement affects the tool and entails a tool movement. Thus, the human information processing system needs two feedback loops for processing movements with tools:

(1) The bodily movement is fed back to the perceived body space (via the proximal movement–effect loop shown as a dashed line). The loop receives its input from such sources as looking peripherally at one's own hands. Even when visual input is unavailable, tactile and proprioceptive perception from the moving hand contributes to the perceived body space. Body space does not have to correspond with the tool space (see below). It is widely accepted that the proximal movement–effect loop is essential for controlling human actions; moreover, that the anticipation of movement effects is used to generate an action plan from the very beginning. This so-called ideomotor principle of action planning holds that agents select, initiate and execute a movement by activating the anticipation of the sensory codes for the movement's effects (Greenwald, 1970; James, 1890; for an overview see Hommel, Müsseler, Aschersleben, & Prinz, 2001).

(2) To control tools successfully, the movement of the effective part of the tool (i.e., in most cases the intended action goal) also needs to be fed back to the agent (via the distal movement–effect loop, indicated with a dotted line). Often the tool does not transform the body movement into a tool movement in a one-to-one manner. Imagine a surgeon operating with a laparoscope inside a patient's body, inserting it through a tiny aperture. This modern surgical technique makes it easier for the patient to recover. But such benefits come along with challenges to the surgeon's motor skills and cognitive abilities. The instrument utilized in minimally invasive surgery functions like a two-sided lever, with the pivot point in the aperture of the patient's body. The relation between movements of the surgeon's hand outside the body and resulting movements of the effective part of the tool inside the patient is therefore rather complex. When the surgeon moves the hand leftwards, the tip of the tool inside the patient's body moves to the right (i.e., the "fulcrum effect"; Gallagher, McClure, McGuigan, Ritchie, & Sheehy, 1998). This inverse transformation is likely to contribute to more tissue damage than in open surgery (Savader, Lillemoe, & Prescott, 1997); it also affects the time to initiate a movement (Kunde, Müsseler, & Heuer, 2007; Müsseler, Kunde, Gausepohl, & Heuer, 2008). The second main feature of this lever transformation is the gain; that is, the relation between the movement amplitude of the hand and the movement amplitude of the tip of the lever. For translational movements (moving the lever back and forth through the pivot point) there is a constant gain of 1. But for rotations (moving the tip of the lever sideways or up and down) the gain is variable, depending on the ratio of the lengths of the load arm and the effort arm (gain anisotropy). Third, the surgeon receives visual feedback on a display somewhere in the operating theater, which is often not spatially aligned either with the surgeon's hand or with the tip of the tool.

The control cycles in Fig. 1 are omnipresent in technical environments, for instance, at computer work stations or when driving a car. Some sensorimotor transformations are easy to perform and occasionally we are even not

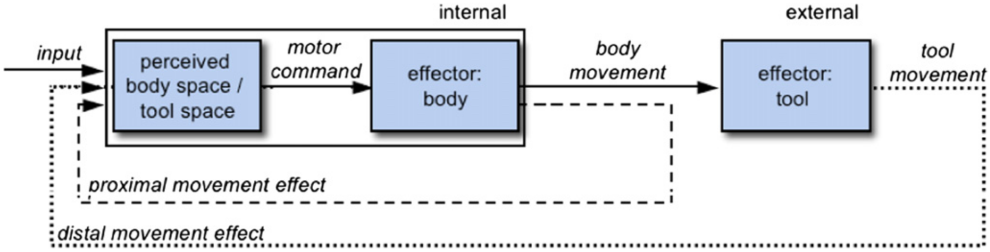

Fig. 1. Tool use requires coordination between proximal movement effects (proprioceptive/tactile feedback from the moving hand) and distal movement effects (visually display movements of the cursor or the tip of the tool).

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aware of them at all (for instance, when using a computer mouse). Other tasks with sensorimotor transformations are extremely difficult to perform. This is often the case when the agent's action produces reversed action effects with the tool, or when the agent is spatially separated from the place where the manipulation takes effect (e.g., in minimally invasive surgery). Consequently, the tool user is confronted with the problem of integrating two different kinds of movement–effect loops. In other words, s/he has to solve the problem of sensorimotor transformation, which is determined by the relationship between bodily movement and movement of the effective part of the tool.

If information from the proximal and distal feedback loops were equally important for controlling actions, any discrepancy between them would be a constant source of interference. The human information processing system solves this problem by favoring information from one feedback loop while attenuating or ignoring information from the other. According to the ideomotor principle, representations of body-related effects, such as the anticipated tactile feedback from the moving hand (proximal action effect) or the anticipated visual effects in external space (distal action effect), may fulfill a generative function in tool use (and in motor control in general). However, recent studies of tool use demonstrate the predominance of the distal action effect (effective part of the tool) as the intentional reference frame for actions with tools (e.g., Kunde et al., 2007; Müsseler et al., 2008; Rieger, Knoblich, & Prinz, 2005; Sutter, 2007). In the next section we will detail the empirical evidence supporting this claim.

2. Dominance of distal action effects in controlling tools

2.1. Tools with simple transformations

In the following we present several studies of the role of proximal and distal action effects when using tools. To introduce a simple sensorimotor transformation, participants usually perform hand movements while different gains for either the *X*-axis or the *Y*-axis perturb the relation between their hand movements and the displayed cursor movements (e.g., Ladwig, Sutter, & Müsseler, 2012; Müsseler & Sutter, 2009; Rieger et al., 2005; Sutter, Ladwig, Oehl, & Müsseler, 2012; Sutter, Müsseler, & Bardos, 2011; Sutter et al., 2008). This is the kind of translational transformation mostly apparent in computer input devices, such as a mouse or touchpad. A representative experimental setup is depicted in Fig. 2. Participants sit in front of a display and a digitizer tablet. A cover screens the tablet and the participant's hand. Thus, participants receive proprioceptive/tactile feedback from their moving hand without visual feedback of the hand itself. The task (e.g., to move the cursor from a start position into a target area) is presented on a display and participants control the cursor via the digitizer tablet and stylus. This is the only visual feedback they receive. In some experimental conditions, the feedback is systematically perturbed by different gains. In accord with recent evidence (see Introduction), it is assumed that distal action effects control tool actions, and that proximal action effects are attenuated or ignored.

Müsseler and Sutter (2009) investigated the proprioceptive/tactile perception of gain changes. The study showed that when using a tool participants were mainly aware of their intended distal action effects, while the proximal action effects were largely neglected. In the experiment different gains for either the *X*-axis or the *Y*-axis perturbed the relationship between the hand movements on the digitizer tablet and cursor movements on the display. As a consequence of the transformation, participants constantly drew circles on the display while their hidden hand movements followed either vertical or horizontal ellipses on the digitizer tablet (Fig. 3). When asked to evaluate their hand movements, participants were extremely uncertain about their trajectories. By varying the amount of visual feedback, the authors were able to investigate the sources of this uncertainty. Findings indicated that the low awareness of one's own hand movements originated mainly from inadequacies in the human tactile and proprioceptive systems, though insufficient spatial reconstruction of this information in memory played an additional role. Thus, even though human agents feel a high degree of motor control when using their hands, and their hand movements are remarkably accurate, they are not very aware of what their hands are doing when they use a tool.

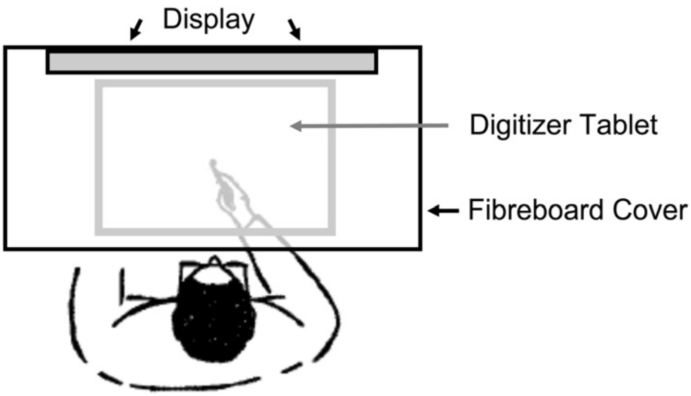

Fig. 2. The standard experimental setup. A cover screens hand movements so that participants receive only proprioceptive/tactile feedback from the moving hand and visual feedback from the moving cursor.

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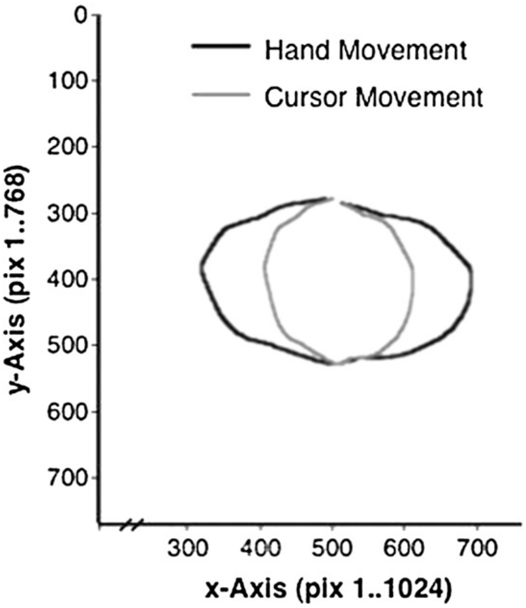

Fig. 3. Typical *XY*-trajectories of the proximal hand movement (black line) and the distal cursor movement on the display (gray line).

The same uncertainty concerning the actions of one's own hand was observed when the distal action effects varied, while hand movements were held constant (Sutter et al., 2008, 2011). Two target boxes were presented on the display, and participants moved the cursor back and forth between the boxes in a smooth and continuous horizontal movement. The movement amplitude of the hand on the digitizer tablet remained constant, while the cursor amplitudes on the display were either 2 times or 4 times longer than the hand amplitudes. In a control condition hand and cursor movement amplitudes were the same. The results showed that with increasing cursor amplitude movement times increased, although participants were performing the very same hand movement throughout the experiment. In other words, as the hand amplitude was held constant distal action effects—the cursor movements on the display—determined motor behavior (see also Rieger et al., 2005). When participants were asked to evaluate their hand movements in a visual adjustment task, estimations of hand amplitudes were quite precise as long as hand and cursor amplitude were similar. When they were dissimilar, estimations of hand amplitudes increased and corresponded to the visual feedback of the cursor amplitude instead of the hand amplitude on the tablet. Thus, again, the findings are consistent with the ideomotor principle and the presumed predominance of distal action effects in controlling tools. During tool use proximal action effects are attenuated or ignored; therefore agents are mainly unaware of what their hands are doing. However, the estimation bias collapsed with high gains: when cursor amplitudes were 4 times longer than hand amplitudes estimates actually decreased. It seems that participants became aware that they had not covered such a long distance with their hand. At this point, estimates corresponded neither to the hand amplitude nor to the cursor amplitude, but settled down between them (see Section 4 for a discussion).

2.2. Tools with complex transformations

In several studies visual predominance was also demonstrated for complex tool transformations: e.g., for inverse transformations (e.g., Kunde et al., 2007; Massen & Prinz, 2007; Müsseler et al., 2008; Müsseler & Skottke, 2011), rotation transformations, and nonlinear transformations (e.g., Heuer & Hegele, 2007, 2008; Heuer & Sülzenbrück, 2009; Proctor, Wang, & Pick, 2004).

As an example we describe experiments investigating whether distal action effect control holds for force-controlled tools (Sutter, 2007; Sutter & Ziefle, 2004, 2006). Force-sensitive joysticks are one example in this regard. The agent manipulates the joystick by applying force with the tip of the finger on the joystick's surface. Pressing rightwards induces a rightward shift of the cursor, and vice versa, while the applied force is transformed into cursor velocity. With force-controlled tools the agent still receives proprioceptive/tactile feedback from the hand (concerning the applied force), but this feedback has a more complex relationship to the distal action effect (cursor movement) than the simple transformations we described in the previous section. In the present experiments target size and target distance on the display were varied according to Fitts' law[1] (Fitts, 1954). Participants performed the aiming task either by operating a touchpad (which, like the mouse, makes a translational transformation) or with an isometric joystick (which makes a force transformation). It was assumed that if movements were controlled by distal action effects movement times should vary as a function of Fitts' law, even when no hand movements were needed to control the isometric joystick.

Fig. 4 depicts mean movement times for the touchpad and the isometric joystick as operated by novices (triangles/dashed lines) and experienced users (squares/solid lines). Movement times were in strong agreement with Fitts' law (adjusted $R^2 \geq .87$). Intercepts differed significantly between touchpad and joystick, indicating generally poorer performance when operating the joystick (Sutter & Ziefle, 2004). Kinematic analysis showed that the cursor trajectories generated by the joystick did not follow a smooth and continuous path, and highly deviated in the target area (Sutter & Ziefle, 2006). Even though cursor control was inefficiently organized with force-controlled tools, the findings demonstrate that distal action effect control also held for them. To a certain degree, cursor control increased with practice (Sutter, 2007; Sutter, Oehl, & Armbrüster, 2011). But discrepancies between motion- and force-controlled devices were still noticeable in experienced users (Sutter & Ziefle, 2004, 2005, 2006).

To sum up, the empirical evidence is in accordance with the ideomotor principle and the presumed predominance of distal action effects in controlling tools. When they use tools proximal action effects are attenuated, so that agents

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[1] Fitts' law predicts movement times (MT) for manual rapid aiming movements on the basis of a log-linear relation between target size (Width W) and target distance (Amplitude A): $\mathrm{MT} = a + b \log_2 (2A/W)$. It is a very robust psychomotor law, which holds for all kinds of manual or transformed movements (e.g., Casiez, Vogel, Balakrishnan, & Cockburn, 2008; Langolf, Chaffin, & Foulke, 1976).

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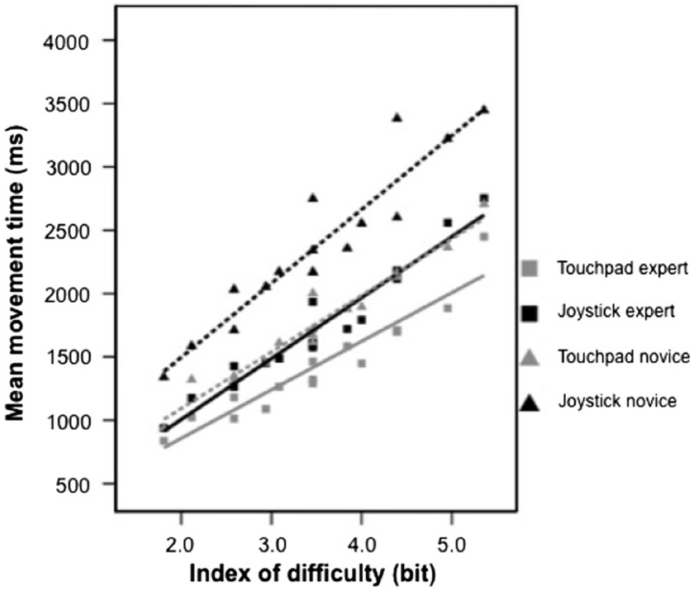

Fig. 4. Mean movement times as a function of target size and target distance (=index of difficulty) for touchpad novices and experts (gray triangle/dashed line and gray square/solid line, respectively) and isometric joystick novices and experts (black triangle/dashed line and black square/solid line).

are mainly unaware of what their hands are doing, while distal action effects dominate action control and influence proprioceptive/tactile perception and motor behavior. This overall bias is independent of the location of the effect variation and of the kind of relation between hand and cursor movement. However, distal effect control is slow, inaccurate, and strenuous when tools with complex and rather artificial transformations are used. Here, the coordination of discordant information from the proximal and distal feedback loop induces costs. This indicates that interference can be reduced at a motor level, but that it remains at a cognitive level of information processing. To a certain degree, this can be overcome by practice, but even after long periods of practice performance discrepancies between tools with easy and complex transformations may persist. This point leads to the next section in which we look at the underlying motor and cognitive processes when people adapt to or learn transformations.

3. Compensation for, adaptation to, and learning of transformed movements

It is often found that people are able to adapt quite well to tool transformations (Ghahramani, Wolpert, & Jordan, 1996; Imamizu et al., 2000; Kagerer, Contreras-Vidal, & Stelmach, 1997; Wolpert, Ghahramani, & Jordan, 1995), although some transformations are easier to learn than others. In general, transformations scaling gain (=visuomotor gain, i.e., the effect amplitude on the display results from a multiplication of the amplitude of the moving hand, for example moving a computer mouse 3 cm results in a cursor movement of 6 cm on the screen) are easy to adapt to (Bedford, 1994; Bock & Burghoff, 1997; Rieger et al., 2005; Seidler, Bloomber, & Stelmach, 2001; Sutter et al., 2008). However, complex transformations, such as nonlinear relationships between movements and effects, are more difficult to acquire (Heuer & Hegele, 2007; Rieger, Verwey, & Massen, 2008; Verwey & Heuer, 2007), and simple adaptation processes are not sufficient. Learning processes—i.e., the acquisition and use of strategies—need to take place in order for people to handle such transformations.

3.1. Compensation for and adaptation to simple transformations

In this section we present empirical data about the integration of discordant perception–action feedback. For instance, Ladwig et al. (2012) found significant shifts in motor behavior after performing transformed movements. Participants were asked to move the cursor horizontally into a target area using a stylus on a covered digitizer tablet. When the cursor was within the target area, the movement direction had to be reversed. Participants were asked to replicate the initially performed hand amplitude as accurately as possible when they moved in the opposite direction after the reversal; they did not receive any visual feedback during this movement. In the first condition (distal effect variation, Fig. 5) the hand amplitudes were held constant, but the cursor amplitudes on the display were shorter or longer than the hand amplitudes. In the second condition (proximal effect variation) cursor amplitudes were kept constant and hand amplitudes were shorter or longer. In a control condition hand and cursor amplitudes were equal. Participants replicated untransformed movements very accurately. When replicating transformed movements their hand amplitudes prominently shifted toward the visual feedback of the initial task: When participants had seen shorter cursor amplitudes the replicated hand amplitudes were accordingly shorter; the

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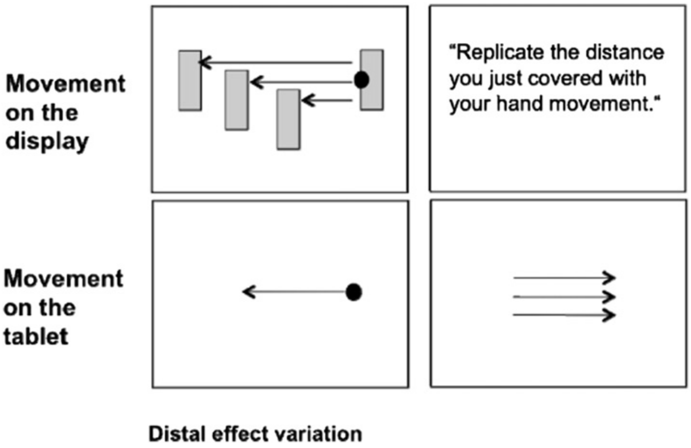

Fig. 5. Reproduction task of closed-loop control.

same went for longer cursor and hand amplitudes. These shifts occurred under both types of effect variation, but were more pronounced when proximal effects varied. The finding indicates that participants did not reproduce movements by simply "recalling" stored information about motor control variables from memory (for an overview see, e.g., Rosenbaum & Krist, 1996). If this had been the case, subsequent movements would have been very exact.

Rieger et al. (2005) showed that introducing a sudden change in gain not only results in short term aftereffects (of the previous gain) and quick compensation, but also that movements are performed differently with different gains even after adaptation. In their experiments participants performed continuous up and down movements between two horizontal lines presented on a display. Hand and tablet were screened from view, while participants received visual feedback in front of them on the display. During six strokes no gain was in effect and participants performed a default amplitude. Then, in some conditions, a gain was introduced, which lasted for another six strokes. This pattern of six strokes with standard amplitude/no-gain and six strokes with an experimental manipulation was repeated several times. Gain intensity in the experimental manipulations was randomly varied. In one condition the cursor amplitude was shorter, equal, or longer compared to the constant hand amplitude (distal effect variation); in another condition the hand amplitude was shorter, equal or longer compared to the constant cursor amplitude (proximal effect variation). Compensation onset was faster with distal effect variation than with proximal effect variation. This was because the information to detect distal effect variations was immediately available to participants, as the target amplitude was displayed on the screen, but the information to detect proximal effect variations needed to be accumulated by comparing several internally predicted distal effects with the observed effects. In addition, Rieger et al. (2005) found faster compensation for reductions in amplitudes than for extensions in amplitudes. This can be explained by a greater need for compensation in amplitude reductions, since not compensating irrevocably leads to overshoot errors under these conditions. Consequently, strategic processes contributed to compensation speed. For distal as well as proximal effect variation, amplitudes shifted toward the visual feedback: participants compensated for shorter cursor amplitudes with shorter hand amplitudes and for longer cursor amplitudes with longer hand amplitudes. Within five strokes participants were nearly completely adapted to the gain change. Most importantly, when they had adapted to gain variations, display amplitudes still had an important impact on movement times. In the distal effect variation condition, movement times increased as a function of display amplitude, although the hand amplitude remained constant. Nevertheless, hand amplitude had an additional influence on movement times (see Section 4 for a discussion).

3.2. Learning of complex transformations

The acquisition of complex transformations is more difficult and time-consuming. Instead of simple adaptation processes, strategic processes need to take place in order for people to handle such transformations (e.g., Heuer & Hegele, 2007, 2008; Rieger et al., 2008; Sülzenbrück & Heuer, 2009, 2010, 2012). Imagine again a surgeon operating with a laparoscope inside a patient's body. The tool functions like a two-sided lever with the pivot point located in the aperture of the patient's body. The fulcrum effect (inverse transformation) and gain anisotropy (variable gain factor for rotations) result in a complex relationship between hand movement and the movement of the effective part of the tool. In a series of experiments Sülzenbrück and Heuer (2009, 2010) investigated the processes of adaptation and learning for this kind of transformation. Participants moved a cursor on a display from a central start position to one of eight possible target locations, using a stylus on a covered digitizer tablet. The positions of the stylus on the tablet and the cursor on the display corresponded to the end points of a two-sided lever. As depicted in Fig. 6, cursor targets were aligned on a circle around the start position (see the black dots in the upper part of Fig. 6). The corresponding targets for the hand were aligned in an egg-shaped form around the start position of the hand (black dots in the lower part of Fig. 6), resulting from the different gain factors depending on target location. Fig. 6 also displays mean movement trajectories (black lines) in a test phase without visual feedback; the test phase took place after an intensive practice phase in which visual information of the cursor movement was continuously available. With perfect adaptation to the transformation, the end positions specified in the instructions (black dots) and the end positions of the movement trajectories (black lines) should have been identical. However, participants were not able to accurately reach the instructed egg-shaped hand target positions, but consistently ended in circularly aligned hand target positions (see Fig. 6, lower part). This demonstrates that participants only partly accounted for the transformation. They adapted to the left–right transformation, and neglected the gain anisotropy, so that the directions of hand movements were directions of the cursor movement reflected on a vertical axis passing the pivot point (Sülzenbrück & Heuer, 2009). Instead of learning the complex visuomotor transformation (represented by the black dots) participants had learned a simplified approximation of this transformation (represented by the open squares).

In another study, Rieger et al. (2008) investigated the ability to adjust to nonlinear transformations. An everyday example of adjustment to a nonlinear transformation is steering a car. Here, an internal model of the transformation allows the driver to determine the steering wheel rotation required to attain a goal specified in terms of lane position and heading angle. The ability to develop internal models of transformations implies that people are able to control systems directly in terms of system output. They can do this even before they start moving (i.e., in open loop mode, which is fast), instead of needing to continuously attend to system output and correct deviations from the intended output (closed loop, which is slow; e.g., Heuer & Hegele, 2007; Massen & Prinz, 2007). In the experiment participants executed rapid aiming movements with five different amplitudes. For the no-transformation group target amplitudes on a display matched target amplitudes on a digitizer tablet. For two experimental groups

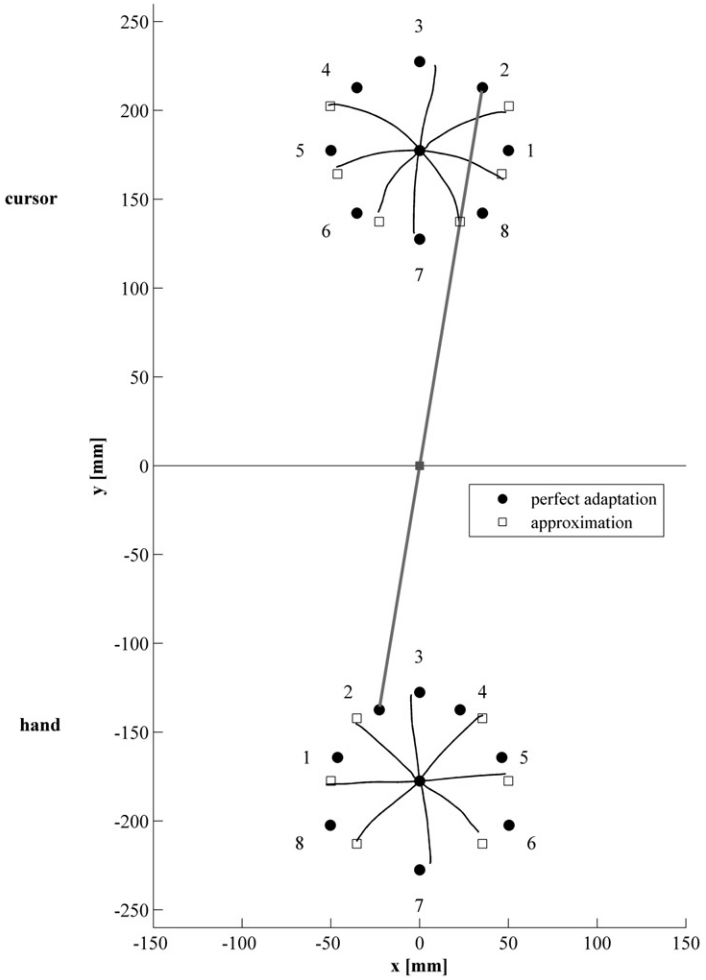

Fig. 6. The central start position and eight possible targets for the hand (lower part) and the cursor (upper part) in the lever transformation are displayed as black dots. For target 2, the position of the lever is shown in gray. The open squares represent the end positions of the simplified approximation (Sülzenbrück & Heuer, 2009).

a nonlinear relationship between the target amplitude on the display and the required movement amplitude of the hand was introduced. In the cursor-same group, participants saw the same target amplitudes on the screen as participants in the no-transformation group, but moved different amplitudes in hand space. Participants in the hand-same group were to produce the same amplitudes as the no-transformation participants in hand space, but were shown different amplitudes in cursor space. After a learning phase, participants adjusted to the external transformation by developing an internal model. The internal model also showed some imperfections: although the overall visuomotor gain for the shortest and the longest amplitude was 1.0 for all three groups, amplitudes significantly differed between groups (e.g., in cursor space both transformation groups produced longer amplitudes than the no-transformation group for the shortest amplitude). Those imperfections are, however, in line with the assumption that the internal model consists of a continuous rule (cf. Verwey & Heuer, 2007) rather than a virtual lookup table of individual stimulus–response mappings for all amplitudes.

Of particular interest in this study was the locus of the internal model. Following Verwey and Heuer (2007), it was assumed that perceptual processes identify the target amplitude in external space. Then amplitude specification translates the perceived target amplitude into a code representing the amplitude that a limb will have to move. The amplitude code is then translated into a movement with a specific velocity–time profile. The locus of operation of the internal model can be determined by assessing the time-course of amplitude generation and trajectory generation using the timed response method. The analyses of relative amplitudes, percentage of amplitude at peak velocity, and amplitude variability all indicated that the internal model operated at or before amplitude specification (for details of the reasoning behind the analysis see Rieger et al., 2008; Verwey & Heuer, 2007). Interestingly the internal model operated at the same processing level with continuous feedback and with terminal feedback (Rieger et al., 2008; Verwey & Heuer, 2007). Thus, at least with rapid aiming movements, the type of feedback may not matter for the internal model's locus of operation. Feedback may however be important in other circumstances (see Section 4). Another interesting result of the study was that even with continuous feedback, explicit awareness of the transformation did not develop. This was the case even though participants were told that there might be a transformation between movements and movement feedback. Some participants reported that "something weird" was going on, but they could not describe the nonlinear relationship. This agrees with other results covered in this review, indicating that the conscious perception of proximal action effects may be attenuated or absent in tool use actions.

In summary, confronting participants with simple transformations or transformation changes results in aftereffects (depending on the previous gain) and quick compensation. Still, even after adaptation movements are performed differently with different gains. The studies demonstrate the predominance of distal action effects as well as the considerable flexibility of the human information processing system in efficiently integrating discordant perception–action feedback, even at the early stages of adapting to a simple transformation. Whether the effect was varied proximally or distally, participants always compensated for it in relation to the produced distal action effect. This is all the more remarkable, because with distal effect variation and constant hand amplitude the purely motor task remains the same (Ladwig et al., 2012; Rieger et al., 2005). Nevertheless, participants made unnecessary attempts to compensate for the change (Rieger et al., 2005) and did not reproduce the actual movements (Ladwig et al., 2012).

The studies on the acquisition of complex tool transformations point to a remarkable capacity of agents to acquire new internal models for different types of tool transformations. Internal models show some specific imperfections (i.e., simplified approximation of movement parameters), however, those imperfections indicate that the internal models consist of a continuous rule rather than individual stimulus-response mappings for different amplitudes (Rieger et al., 2008; Sülzenbrück & Heuer, 2009). It is not clear, whether those imperfections would disappear with longer training sessions than those conducted in the experiments. In any case, the imperfections indicate that certain aspects of a transformation may be easier to learn than others. For instance, when using a lever the inverse transformation is easier to learn than gain anisotropy (cf. Sülzenbrück & Heuer, 2009). Interestingly, explicit awareness of the actual actions did not develop with complex transformations any more than it did with simple transformations (Rieger et al., 2008).

4. Limits in distal action effect anticipation

As has been shown in the previous section, the predominance of distal action effects can be observed in tools with both simple and complex transformations. However, the ability to integrate discordant perception–action feedback has its limits, especially, but not only, with complex transformations. Recall the task introduced by Ladwig et al. (2012): Different gains for the *X*-axis perturbed the relation between hand and cursor movements (Fig. 5). When participants were asked to replicate their hand movements without visual feedback, hand amplitudes varied in accordance with the displayed amplitudes. We concluded that hand movements were assimilated to visual cursor motions. Adding a second transformation (in one case, a 90° rotation of visual feedback, in another a 180° rotation of the same visual feedback) did reduce the aftereffects, but only when discrepancies between hand and display amplitude were most obvious. In this case participants were fully aware of the proximal action effects and reproduced their initial hand amplitudes exactly.

A similar shift toward the proximal action effects was observed when visual feedback of hand movements was transformed (Sutter & Ladwig, 2012; Sutter & Müsseler, 2010). In the experiments, participants did not use a tool with a sensorimotor transformation, but visual feedback of stimuli and hands were transformed by reflection at the *X*-axis, at the *Y*-axis, or at both axes. This introduced different

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stimulus–response (S-R) mappings between the visually perceived stimuli and hand movements on the display, and the proprioceptive/tactile feedback from the moving hand on the table. Results showed that mostly distal S-R mappings controlled behavior. Performance was about as good with an egocentric or a non-egocentric view so long as the left–right relations corresponded with the body space (i.e., when there was no transformation or an *X*-axis reflection). Interference occurred when visual feedback was reflected at the *Y*-axis or at both axes, so that performed left-side movements were seen as right-side movements and vice versa. Again, agents relied on visual information until the discrepancy between visual and proprioceptive information was most obvious—when they received inverse feedback from a non-egocentric view (reflection at both axes). Then, the importance of distal S-R mappings diminished, with the consequence that compatible mappings between proximal hand positions and displayed stimuli accounted for faster responses than compatible mappings between displayed hand positions and stimuli. It seems that with extreme discrepancies or even opposite perception–action feedback the information processing system is no longer able to attenuate conflicting information. The agent becomes fully aware of the proximal action effects, which now dominate action control in place of the distal action effects.

Further evidence for limits to distal action effect anticipation comes from Sülzenbrück and Heuer (2009, 2010). They demonstrated that visual effects dominated the development of the internal model. However, in a further experiment (Sülzenbrück & Heuer, 2010), they showed that the impact of distal action effects could be overcome in the course of practice, if the endpoint errors associated with the approximation became more evident. With terminal visual feedback and a different target configuration (with larger distances between the target locations and targets of the approximation than in the first experiment), endpoint errors shrank in the course of learning, and participants actually adapted to the visuomotor transformation of the lever. These findings show that the dominance of distal effects is subject to boundary conditions; for example, the type of visual feedback available during practice. Terminal visual feedback seems to be a likely candidate to attenuate the dominance of distal action effects, in contrast to movements in which visual information about the effect is continuously available.

Even with simple transformations, movements are dominated by the distal effects but only partially determined by them. For example, required movement amplitudes (proximal) have an additional effect on movement parameters (Rieger et al., 2005). One might be tempted to attributes this to a conflict between distal and proximal effects, which puts a limit to adapting to a transformation solely based on visual coordinates. However, as participants are usually not aware of simple transformations after adaptation, it is an unlikely explanation. The influence of movement amplitude (proximal effects) with simple gain transformations is best explained by the fact that the control of movement in distal effect coordinates is limited by structural constraints imposed by the inherent characteristics of the body as a mechanical system. Neuromuscular constraints further limit movement organization in reference to distal action effects (Rieger et al., 2005).

5. Conclusions

Tool use has been an important step in human evolution. And with increasing technological advancement, more diverse and more complex tools are constantly being developed. Skilled tool use enables humans to interact successfully with the environment. When controlling tools with sensorimotor transformations the agent has to integrate proprioceptive/tactile information from the moving hand with visual feedback from the effect in distal space. The perception–action feedback sometimes does not correspond or is even in conflict. Consequently, integrating information concerning the moving hand and the moving effective part of the tool presents a challenge to agents when they use tools. The successful execution of actions with tools depends particularly on:

- the complexity (and transparency) of the transformation, including:
    - the direction between body movement and tool movement (e.g., inverse tool transformation)
    - the gain factor and its variability (e.g., gain anisotropy)
    - the perspective from which tool actions are monitored (e.g., indirect view)
- the biomechanical constraints of the body
- cognitive/information processing constraints
- the stage of learning (i.e., adaptation, or acquisition of an internal model).

This review has presented results from studies in which simple and complex transformations were investigated. Many of these transformations, though non-transparent, had a high feature overlap between vision and proprioception; for instance, controlling a mouse/stylus on a digitizer tablet. Although different gains perturb the relation between hand and cursor movement, the transformation is simple and agents more or less automatically adapt to this kind of change. This is not the case for tools with complex transformations, in which there is a low feature overlap. For instance, when controlling a two-sided lever the agent has to learn an unfamiliar relationship between hand movements and movements of the effective part of the lever. This is a time-consuming process and human behavior often becomes slow, inaccurate, and strenuous.

We further showed that distal action effects play a prominent role in tool use, in accordance with the ideomotor principle (Greenwald, 1970; James, 1890). If vision and proprioception do not correspond the human information processing system favors the intended distal action effects while ignoring or attenuating the proximal action effects. This in turn results in reduced awareness of the actions of our own hands when we are using tools. The reduced awareness of one's own actions is functional: if information from both feedback loops were equally important, proximal and distal effects would be constantly interfering with each other.

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However, the dominance of distal action effects is subject to boundary conditions. With extreme discrepancies between proximal and distal effects, distal action effects no longer dominate action control, but tool users become fully aware of the proximal action effects. We assume that switch is also modulated by the agent's awareness of the sensorimotor transformation. The information available to an agent may be an important factor for awareness. For instance, varying the amount of visual feedback during practice either results in action control based on distal effects (continuous visual feedback) or in control based on proximal effects (terminal visual feedback; Sülzenbrück & Heuer, 2009, 2010). Further evidence for this hypothesis comes from research on adaptation to prism goggles. For example, Uhlarik and Canon (1971) proposed that where with continuous visual feedback attention is focused on visual input, terminal visual feedback directs attention toward kinesthetic information. Without visual input, proprioception alone can result in accurate perception of limb movements; however, the impact of proprioception is diminished when visual input is available (Hay, Pick, & Ikeda, 1965). Proteau and Isabelle (2002) showed that during visible movements proprioception is not attended to, which even seems to coincide with reduced firing rates of muscle spindles (Jones, Wessberg, & Valbo, 2001). The processing of proprioceptive feedback could thus be masked by the processing of visual feedback (Tremblay & Proteau, 1998).

In conclusion, the dominance of distal action effects in action control with tools is a major precondition for controlling tools successfully. It allows for a wide range of flexible sensorimotor adaptations and—what may be more important—it gives us the feeling of being in control. However, this mechanism seems to be subject to boundary conditions, as it breaks down with extreme discrepancies in perception–action feedback. When discrepancies are extreme, agents become fully aware of the conflict in information processing and human behavior becomes slow and error-prone. Moreover, action control mostly based on distal action effects shifts to control based on proximal action effects. Thus, action–effect control principles play an important role for understanding the constraints on acquiring and dealing with tool transformations.

Acknowledgments

We thank Laura Makowski for research assistance. This research was supported by a grant from the German Science Foundation to Christine Sutter and Jochen Müsseler (DFG Su 494/4).

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